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# Evaluation of Dynamic Daylight Metrics
## Based on Weather, Location, Orientation and Daylight Availability

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*ABSTRACT: This paper demonstrates that it is possible to achieve 3 daylight credits of Leadership in Environmental and Energy Design version 4 (LEED v4) in all latitudes and orientations. This study uses a space with sidelight windows and shading devices representing a section of a typical office in a multistory building. To comply with LEED v4, the space has been simulated under different weather, location, orientation, and daylight availability conditions. Simulations were done using the DIVA-for-Rhino and Grasshopper plugins. Twelve selected locations with their vertical facades facing the cardinal directions were simulated. The design variables were window size, geometry, and optical properties of the shading devices. Findings show that to comply with the Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) metrics of LEED v4 daylight credits, the south-facing facades require minimum shading devices in low latitude locations (0°–25°), extended shading in intermediate latitudes (25°–50°), and shading that extensively blocks the window glass in high latitudes (> 50°). In general, north-facing facades do not require shading except at equatorial locations. East- and west-facing facades at all latitudes require extensive shading devices similar to south-facing facades in high latitudes.*
*KEYWORDS: Daylighting, Metrics, Parametric Design, LEED v4, High-low Latitudes*

**1. INTRODUCTION**

On average, most people spend more than 90% of their time indoors and, in consequence, are often exposed to poor lighting, both in terms of quality and quantity. Many studies have shown the benefits of good daylighting in buildings, including as social benefits (well-being and health) and economic benefits (energy savings and increased productivity). Daylighting experts have studied in detail the quantity and quality of daylighting in spaces, and have created daylighting metrics and standards to evaluate the daylighting performance based on occupants' preferences. These standards and metrics promote successful daylighting in buildings, help designers create visually comfortable spaces, and help manufacturers develop technologies that save energy and satisfy consumer needs. [1]

In 2012, the Illuminating Engineering Society released the LM-83-12 standard [2], an approved method for Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) metrics for daylighting performance in new and existing buildings. This standard is based on a field study of 61 spaces in six cities in the United States from the states of California, Washington and New York, within latitudes 37° to 47° for the California Energy Commission (CEC) [1]. The LEED program adopted the use of sDA and ASE as one of the two compliance paths for the daylight credit for the LEED v4, which was released in 2014. [3] The credit requires a minimum of 300 lux for sDA for at least 50% of total occupied hours of the year, for (1) 55% of floor area, for 2 LEED credits, and (2) 75% or more the occupied floor area, for 3 LEED credits (sDA-300lux, 50% hours); no more than 10% of regularly occupied spaces can exceed 1000 lux of direct sunlight for more than 250 hours per year (ASE 1000 lux, 250 hours). After LEED v4 was released, an addendum was added that increased the maximum ASE to 20%. In 2018, the U.S. Green Building Council (USGBC) called for proposals to improve the new LEED v4.1, more than 250 proposals were submitted by industry stakeholders. [4] The LEED v4.1 daylight credits [5] incorporated these proposals, lowering the requirements: the ASE metric was removed (even though the CEC study reported that occupants were less satisfied with ASE > 20%), and added 1 credit to spaces with sDA-300lux over a lower threshold of 40% of floor area. (Table 1)

*Table 1: LEED v4 Metrics and Points.*

| LEED v. (year) | Metric | Points |
|---|---|---|
| 4.0 (2014) | sDA300/50% > 0.55, 0.75, 0.9<br>ASE1000,250 < 10% | 1-3 |
| 4.0 Add. (2017) | sDA300/50% > 0.55, 0.75, 0.9<br>ASE1000,250 < 20% | 1-3 |
| 4.1 (2019) | sDA300/50% > 0.4, 0.55, 0.75<br>If ASE1000,250 > 10%, identify how the space is designed to address glare. | 1-3 |

This paper demonstrates that it is possible to achieve the 3 daylight credits of LEED v4 in latitudes ranging from 0° to 62° in the Northern Hemisphere.

## 2. METHODOLOGY

For this study, 12 locations were selected (see Table 2). These locations represented a wide variety of climates from hot and humid to cold and snowy, and from very sunny (Phoenix) to overcast skies (Anchorage). For the purpose of this study, latitudes from 0° to 25° are considered low, 26° to 50° are considered intermediate, and > 50° are considered high. The building locations in the CEC report [1] are within the intermediate latitudes of this study.

A typical office space in any of these 12 locations was modelled in Rhino 6 and linked to a Grasshopper script. Simulations were conducted with DIVA-for-Rhino v4 [6] and RADIANCE [7] in order to generate climate-based annual hourly illuminance data for 200 sensors at 0.76 m height. About half of the simulations were conducted manually using principles of effective shading design. The other half used a parametric approach.

*Table 2: Locations, latitude and sunshine hours [8]*

| Location | Latitude | Sunshine hours |
|---|---|---|
| Quito | 0.1 | 2,238 |
| Caracas | 10.6 | 2,507 |
| Puerto Rico | 18.4 | 2,701 |
| Miami | 25.8 | 3,154 |
| Houston | 30.0 | 2,578 |
| Phoenix | 33.4 | 3,872 |
| San Francisco | 37.6 | 3,062 |
| New York | 40.7 | 2,535 |
| Boston | 42.3 | 2,634 |
| Seattle | 47.4 | 2,170 |
| Edmonton | 53.6 | 2,345 |
| Anchorage | 61.1 | 2,061 |

### 2.1 sDA and ASE simulations

sDA and ASE are two important evidence-based annual daylighting performance metrics. It is the result of a six-year research effort of the Illuminating Engineering Society (IES) Daylight Metrics Committee led by the Heschong Mahone Group. [9] The sDA evaluates if a space receives enough daylight (> 300 lux) during regularly occupied hours (8:00 to 18:00) on an annual basis over a horizontal work plane. ASE intends to limit excessive sunlight in a space. ASE measures the presence of sunlight using annual hourly horizontal illuminance grids rather than luminance measures.

The office space was modelled with a sidelight window on one facade that represents a section of a deep open plan office space of 3.0 m high, 6.0 m wide, and 9.1 m long. The window's width varies from 5.5 m to 6.1 m, and the window's height from 1.5 m to 2.3 m. The window's visible transmittance (Tvis) is 70% and the window-to-wall ratio (WWR) ranges from 0.45 to 0.75. The interior surface reflectances are 70% for the ceiling, 70% for the walls, 70–90% for the shading, and 35% for the floor. No blinds were used in the simulations. The Radiance ambient parameters were: -aa .15 -ab 5 -ad 2048 -ar 512 -as 1024 -dr 2 -ds .2 -lr 6 -lw .004 -dj 0 -sj 1 -st 0.15.

### 2.2 Annual Incident Daylight

The cumulative daylight illuminance on unobstructed vertical facades facing the cardinal directions and on the flat roof of a building [10] was calculated in DIVA-for-Rhino for the 12 locations. This calculation indicates which locations and facades receive higher or lower daylight illuminance throughout the year. Data were calculated hourly using Perez skies based on EnergyPlus (EPW) weather files, considering sun, sky, and ground (20% reflectance).

### 2.3 Shading design, projection factor, and view angles

The Ladybug Tools [11] were used to design the shading devices for the 48 facades based on the incident solar radiation, generated from local climate EPW weather files. Fig. 1 depicts the radiation intensity distribution over a skydome for low, intermediate, and high latitudes. Angles for the horizontal and vertical shading devices were defined for the 12 locations, in order to reduce the number of iterations for the parametric runs of the east- and west-facing facades, and for the manual runs of the south- and north-facing facades.

In this paper, the dimensions of the horizontal and vertical shading devices are defined as horizontal and vertical projection factors (PF). The horizontal PF is the ratio of the horizontal depth of shading device divided by the height of the window. The vertical PF is the ratio of the vertical depth divided by the width of the window. The horizontal View Angle (hVA) is the angle measured from a normal line to the facade plane on the window sill and the edge of the horizontal shading device. The vertical view angle (vVA) is the angle measured from the edge of the window opposite to the vertical shading device and the edge of the vertical shading device.

## 3. RESULTS AND DISCUSSION

The results of this study are presented as the three types of variables that designers use: context variables (daylight availability), performance variables (sDA & ASE), and design variables (window size, shading geometry, and optical properties of building materials).

### 3.1 Context variables: daylight availability

Fig. 2 presents the cumulative incident daylight for the 12 locations. In south-facing facades, the annual incident daylight is high (108–138x$10^6$ lux-hours) in intermediate (30°–50°) and high latitudes (> 50°), except in locations with predominantly overcast conditions, such as Seattle and Anchorage (83–94x$10^6$ lux-hours). South-facing facades in latitude 0° receive an annual incident daylight of 72x10$^6$ lux-hours, which is fairly low compared with the amount received on a flat roof, which is three times higher.

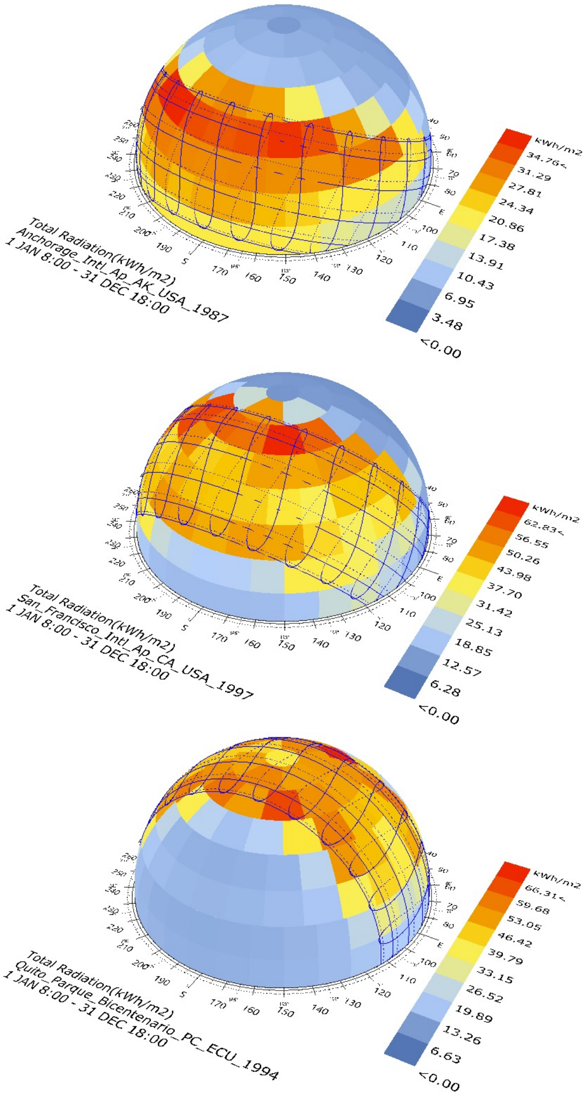


*Figure 1: Solar Radiation at Anchorage AK (top), San Francisco CA (center), and Quito, Ecuador (bottom).*

In north-facing facades, the cumulative incident daylight illuminance gradually decreases from low latitudes to high latitudes. For example, a north-facing facade in Anchorage receives one-third the daylight received in Quito. The cumulative incident daylight in south-facing facades is four times higher than in north-facing facades in Phoenix and Edmonton, while in Quito the incident daylight in north- and south-facing facades are similar. The lowest incident daylight in east- and west-facing facades are in Anchorage, which receive about half the amount received in Phoenix and Quito.

### 3.2 Performance variables: sDA and ASE

Fig. 3 depicts a summary of the results. sDA > 75% was achieved in all latitudes and orientations (48 cases), even though the annual incident daylight varied from 26x10$^6$ lux-hours (Anchorage, north facade) to 138x10$^6$ lux-hours (Phoenix, south façade; see Fig. 2). The lowest ASE values (almost 0) are reached in intermediate and high latitudes in northern facades, and in all other locations and orientations the ASE values were < 10%.

Fig. 4 presents the sDA and ASE distribution at low (Quito), medium (Phoenix), and high latitudes (Anchorage). Quito has the highest and most uniform sDA distribution in the north- and south-facing facades, and receives the lowest sDA in the east- and west-facing facades. As expected, the lowest ASE values are achieved in the intermediate and high latitudes of the north-facing facades. All the other facades receive 1,000 lux for more than 250 hours in areas adjacent to the window walls, except for the east-facing facade in Phoenix, where sunlight penetrates deep in the center of the space. Shading in the east- and west-facing facades are the most difficult to design to control the entrance of sunlight.

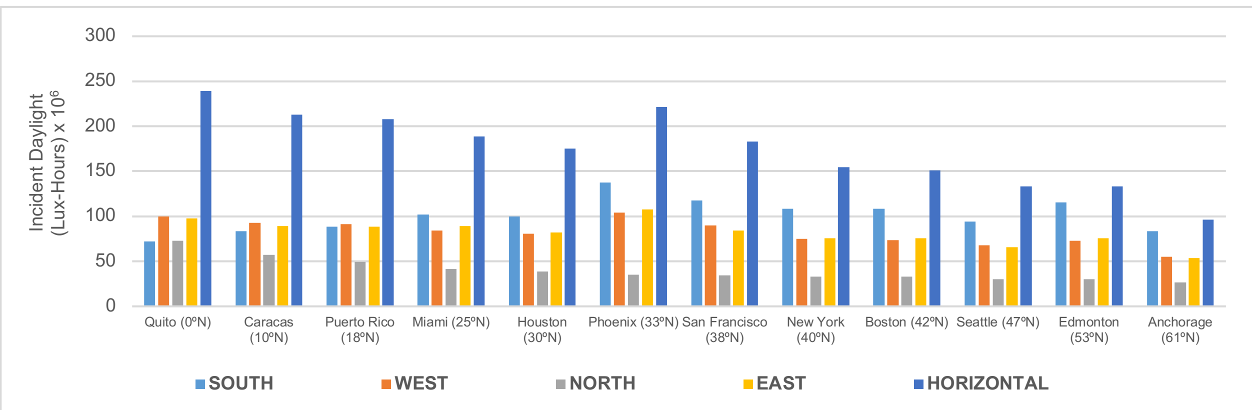


*Figure 2: Total Annual Incident Daylight on different surfaces of a building of the twelve locations.*

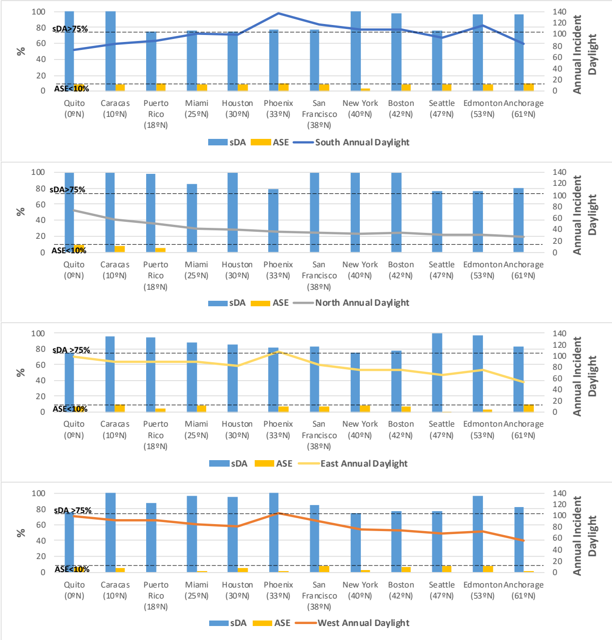


*Figure 3: sDA and ASE results compared with Annual Incident Daylight of all orientations at the twelve locations.*

### 3.3 Design variables: window size, reflectances, projection factors, and view angles

*Window Size*: Table 3 presents the area of windows expressed as WWR. The WWR is the percentage area determined by dividing the building's total glazed area by its exterior wall area. The size of the windows was increased from low latitudes to high latitudes to achieve sDA > 75%. North- and south-facing orientations had the smallest windows (WWR 0.45). In most cases, the window size in the east- and west-facing orientations had medium sized windows (WWR 0.57), except in high latitudes. Due to the depth of the space, the most used WWR was 0.57 in 58% of all cases, and the WWR of 0.45 was used in 25% of all cases. Larger windows were used in high latitudes (47°–53°). For example, the WWR was 0.75 in Anchorage. Large windows in high latitudes with predominantly cold climates may create a problem for energy efficiency. These locations would require advanced glazed technologies with very low U-values.

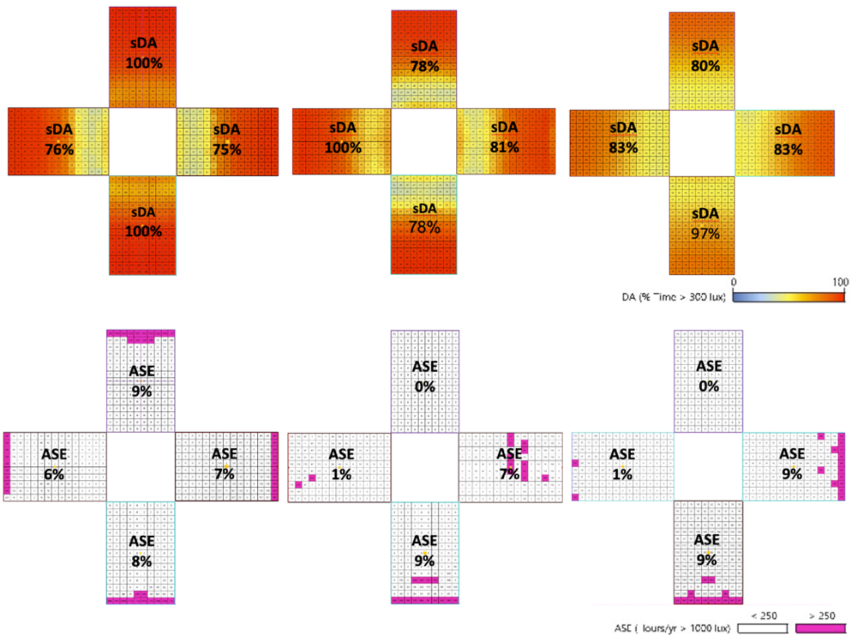


*Figure 4: sDA (top) and ASE (bottom) distribution at four orientations at low (left), medium (center) and high latitudes (left).*

*Table 3: Window-to-Wall Ratios by latitude & orientation*

| Latitude | South | North | East | West |
|---|---|---|---|---|
| 0.1 | 0.45 | 0.45 | 0.57 | 0.57 |
| 10.6 | 0.45 | 0.45 | 0.57 | 0.57 |
| 18.4 | 0.45 | 0.45 | 0.57 | 0.57 |
| 25.8 | 0.45 | 0.45 | 0.57 | 0.57 |
| 30.0 | 0.45 | 0.57 | 0.57 | 0.57 |
| 33.4 | 0.45 | 0.45 | 0.57 | 0.57 |
| 37.6 | 0.45 | 0.57 | 0.57 | 0.57 |
| 40.7 | 0.57 | 0.57 | 0.57 | 0.57 |
| 42.3 | 0.57 | 0.57 | 0.57 | 0.57 |
| 47.4 | 0.57 | 0.57 | 0.7 | 0.7 |
| 53.6 | 0.57 | 0.57 | 0.7 | 0.7 |
| 61.1 | 0.7 | 0.75 | 0.75 | 0.75 |

*Shading Geometry and Material Properties*: Fig. 5 shows horizontal and vertical PFs by orientation of all locations. PF shows to what extent a window is blocked from daylight by external shading; hence the higher the PF, the lower the sDA and ASE. It is noticeable that PFs for south-facing facades increase with the latitude from 0° to 62°. South-facing facades in low latitudes locations (0°–25°) require minimum shading devices (PF Horizontal 0.2–0.6, PF Vertical 0–0.2) to comply with the sDA and ASE metrics; intermediate latitudes (25°–50°) require extended shading (PFH 1–1.8, PFV 0–0.5); and high latitudes (> 50°) require shading that would extensively block the window glass (PFH 1.8–2.4, PFV 0.3–0.4), similar to east-facing (PFH 0–2.4, PFV 0.2–1.1) and west-facing facades (PFH 0–1.6, PFV 0.2–0.8). North-facing facades do not require shading except at equatorial locations (PFH 0.2, PFV 0).

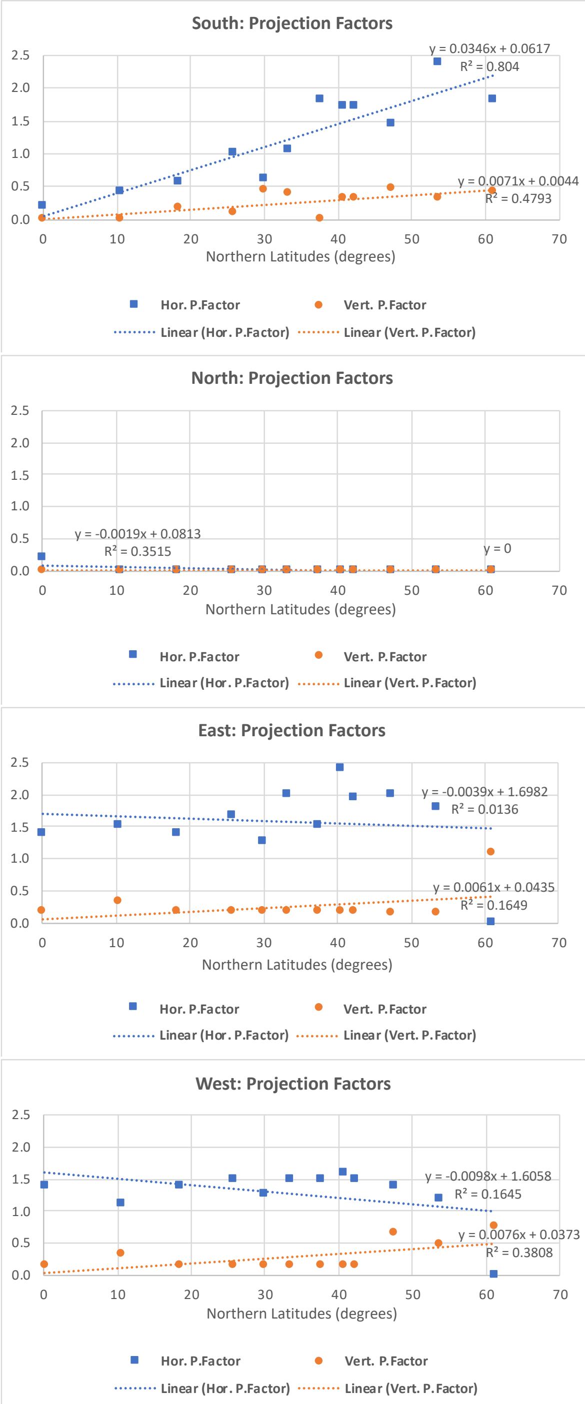


*Figure 5: Horizontal and Vertical Projection Factors for the four orientations.*

Table 4 presents a summary of the reflectances used in shading devices by latitude and orientation. South- and west-facing facades used mostly 70% reflectance in low and intermediate latitudes, but up to 90% in high latitudes. The north-facing facade in Quito used a 70% reflectance. The only facades that needed specular reflectors to pass the sDA > 75% requirement were the east- and west-facing facades in Anchorage.

*View Angles*: As the researcher expected, the trend lines of view angles are inversed to those of the PFs (see Fig. 6). South-facing facade hVAs decrease from 79° to 29° from low to high latitudes. This is caused by the lower angles of the sun and deep shading devices. On the other hand, vVAs decrease from 90° to 68°. East- and west-facing facade hVAs decrease from 23° to 43° from low to high latitudes and the vVAs vary from 62° to 81°. North-facing facade hVA and vVA remain at 90° in all locations, except for Quito.

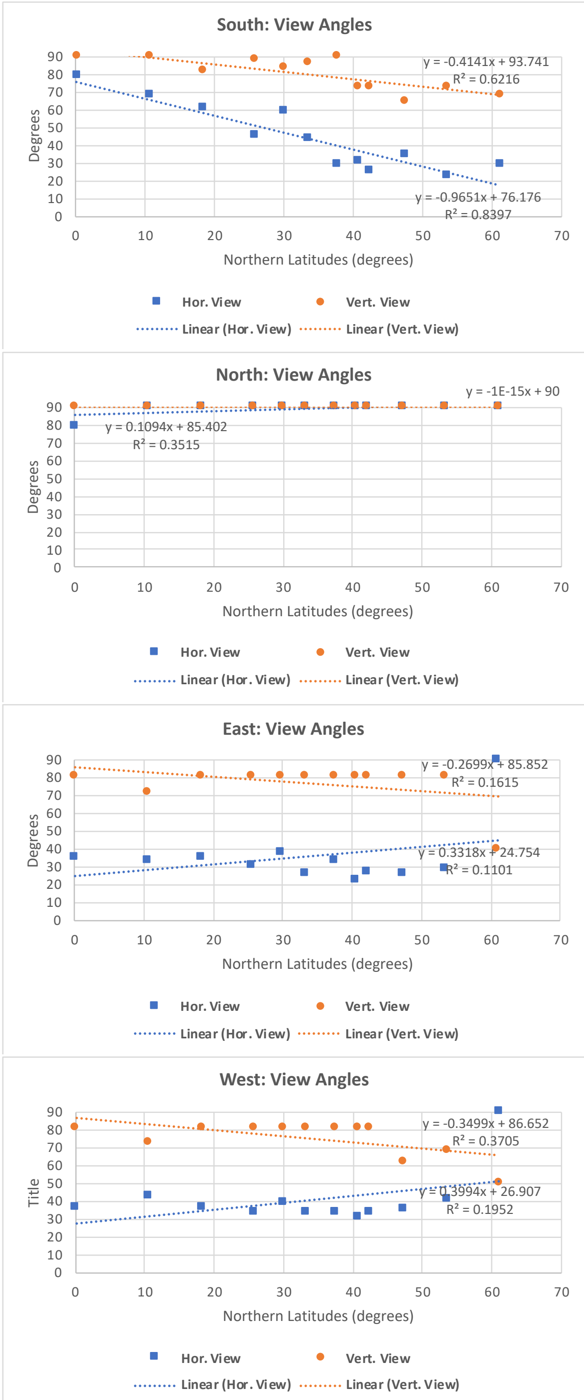


*Figure 6: Horizontal and vertical view angles of four orientations.*

*Table 4: Reflectance (%) of shading devices by latitude & orientation*

| Latitude | South | North | East | West |
|---|---|---|---|---|
| 0.1 | 70 | 70 | 70 | 70 |
| 10.6 | 70 | - | 70 | 70 |
| 18.4 | 70 | - | 70 | 70 |
| 25.8 | 70 | - | 70 | 70 |
| 30.0 | 70 | - | 70 | 70 |
| 33.4 | 70 | - | 70 | 70 |
| 37.6 | 70 | - | 70 | 70 |
| 40.7 | 70 | - | 90 | 70 |
| 42.3 | 70 | - | 90 | 70 |
| 47.4 | 70 | - | 90 | 90 |
| 53.6 | 90 | - | 90 | 90 |
| 61.1 | 90 | - | SheetMetal | SheetMetal |

The shading geometry used in this study can be replicated using the Horizontal and Vertical PFs (PFH and PFV) and material properties presented in Fig. 5 and Table 4.

## 4. CONCLUSIONS

This study demonstrates that it is possible to achieve the 3 points of the LEED v4 daylight credits for north-, south-, east- and west-facing facades at locations within latitudes 0° and 62°. Although the sDA and ASE metrics were developed using spaces located in latitudes 37° to 47°, these metrics can be used in any latitude, whether skies are sunny or overcast, and in all orientations, to allow designers to predict the quantity and quality of daylit spaces.

Shading devices and windows have to be designed according to the requirements of solar geometry by orientation and weather conditions. Results demonstrate that south-facing facades in low latitudes locations (0°–25°) require minimum shading devices to comply with the sDA and ASE metrics; intermediate latitudes (30°–50°) require extended shading devices; and high latitudes (> 50°) require deep shading that would extensively block the window glass, similar to the shading for east- and west-facing facades. In summary, south-facing facades in high latitudes, and east- and west-facing facades at any latitude require the development of articulated facade integrating deep shading devices, reflectors, view windows, and large window areas.

By removing the ASE requirement and giving points to sDA-300lux to 40% of the space, the new LEED v4.1 promotes the use of large expanses of glass and does not encourage designers to harvest daylight to interior working environments. This paper concludes that IES LM-83-12 implemented in LEED v4 is a metric that can be achieved in any latitude and will be able to provide visually comfortable spaces.

Parametric runs without a clear understanding of solar geometry and local climate are not useful to design shading devices and effective windows. With few manual runs, compared to hundreds of parametric runs, we can achieve the LEED v4 sDA and ASE requirements. It is more important to have a clear shading strategy than making guesses using parametric tools.

To increase the sDA in spaces in deep floor plans, other daylighting strategies can be integrated to the daylighting system that could increase the sDA to 100%. Core sunlighting technologies are a good alternative to passively introduce natural light to distances beyond 9 m. [12]


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